CP-Violating Observables in Tagged $D^0/\bar{D}^0$ Decays

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Abstract

We perform a systematic study of CP-violating observables in $D^0/\bar{D}^0$ decays. We show that given a final state, which may be a CP eigenstate or not, all the observables can in principle be measured if decay-time information is available and if, for CP non-eigenstates, both decay rates into f and $\bar{f}$ are considered. As an illustration of our analysis we discuss an effective superweak scenario.

1 Introduction

The study of mixing and decays of neutral D mesons is an important testing ground for the Standard Model (SM), with the potential for discovery of new physics. (See, for instance, refs. [1, 2, 3].) In the SM, short-distance contributions to mixing arise from the box diagrams [4], and are negligible [5]: $\Delta m_D^{\mathrm{box}}(SM) \approx 10^{-17}$ GeV. Initially, it was thought that long-distance effects arising from second-order weak interactions with mesonic intermediate states would give a much larger contribution, about two orders of magnitude larger than the short-distance one [6]. It was later argued by Georgi [7] that cancellations occur among the various dispersive channels, making the overall long-distance contribution smaller than initially estimated. Recently, this conjecture has been confirmed by an analysis of D^0–$\bar{D}^0$ mixing in the framework of heavy quark effective field theory (HQEFT) including leading order QCD corrections [8], which gave $\Delta m_D^{\mathrm{HQEFT}}(SM) \approx (0.9-3.5)\cdot 10^{-17}$ GeV. One concludes therefore that the observation of D^0–$\bar{D}^0$ mixing at any existing or planned facility would be evidence for physics beyond the SM.

The study of D^0–$\bar{D}^0$ mixing also provides the exciting possibility of detecting new sources of CP violation beyond the Kobayashi-Maskawa (KM) mechanism of the SM.

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Indeed, most of the models beyond the SM which predict significant contributions to D^0–$\bar{D}^0$ mixing contain new sources of CP violation. Recently, it has been emphasized that CP violation can play an important rôle in the study of D^0–$\bar{D}^0$ mixing [9, 10, 11].

In this paper we perform a systematic study of a class of physical observables which can provide evidence for CP violation in the D^0–$\bar{D}^0$ system. We then assume (as was also done in refs. [9, 11]) that the dominant new source of CP violation in the D^0–$\bar{D}^0$ system arises from an effective superweak interaction (ESI) leading (in a suitable phase convention) to a non-vanishing Im M_{12}, while Γ_{12} and the decay amplitudes are dominated by the SM contributions, and are real (we neglect small phases in the KM matrix proportional to λ^4 in the Wolfenstein parameterization). Although this is a specific assumption, it turns out that a large number of models which can lead to significant D^0–$\bar{D}^0$ mixing belong to the ESI class [12]. Our analysis is complementary to the work of ref. [13], where an opposite assumption was made, namely that physics beyond the SM contributes significantly only to the decay amplitudes.

We will start by identifying CP-violating observables in tagged $D^0/\bar{D}^0$ decays to specific final states, like CP non-eigenstates $f/\bar{f}$, and CP eigenstates F. We do this by studying the behaviour of various quantities under phase redefinitions of the state vectors. We point out that the study of the time-dependent decay rates of D^0 and $\bar{D}^0$ to a final state f *and* its antiparticle state $\bar{f}$ can, at least in principle, allow the measurement of all the CP-violating observables which we have identified. The same is true in the case of decays to CP eigenstates. Furthermore, after having switched to an ESI scenario, we consider $f = K^-\pi^+/\bar{f} = K^+\pi^-$ and $F = K^+K^-$ as illustrative examples and possible candidates for an experimental search for CP violation.

2 Phenomenology of CP-violation in tagged $D^0/\bar{D}^0$ decays

We want to describe the decays of D^0 and $\bar{D}^0$ to a final state $|f>$ and its antiparticle state $|\bar{f}>$. We first assume that $|f>$ is not a CP eigenstate. Phenomenologically, there are four independent amplitudes

$$\mathcal{A}(D^0 \to f) \equiv \mathcal{A}\,,\ \mathcal{A}(\bar{D}^0 \to \bar{f}) \equiv \bar{\mathcal{A}},\ \mathcal{A}(\bar{D}^0 \to f) \equiv \mathcal{B}\,,\ \mathcal{A}(D^0 \to \bar{f}) \equiv \bar{\mathcal{B}}, \tag{1}$$

entering in the description of those decays. The mass eigenstates of the charmed neutral mesons are

$$\begin{aligned} |D_H> &= p|D^0> + q|\bar{D}^0>\,, \\ |D_L> &= p|D^0> - q|\bar{D}^0>\,, \end{aligned} \tag{2}$$

with $|p|^2 + |q|^2 = 1$ and

$$\frac{q}{p} = \frac{\Delta m - \frac{i}{2}\Delta\Gamma}{2(M_{12} - \frac{i}{2}\Gamma_{12})} = \frac{2(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)}{\Delta m - \frac{i}{2}\Delta\Gamma} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}\,, \tag{3}$$

where $\Delta m = m_H - m_L > 0$ (H=heavy, L=light), $\Delta\Gamma = \Gamma_H - \Gamma_L$, and $M_{12} - \frac{i}{2}\Gamma_{12}$ is the off-diagonal matrix element in the effective time evolution in the D^0–$\bar{D}^0$ space. The sign of the square root in eq. (3) is chosen such that $\Delta m > 0$.

In quantum mechanics, physical quantities cannot depend on the phases of the initial and final states. In our case, physics is therefore invariant under the phase redefinitions

$$|D^0> \to e^{i\gamma}|D^0>\,,\ |\bar{D}^0> \to e^{i\bar{\gamma}}|\bar{D}^0>\,,\ |f> \to e^{i\gamma_f}|f>\,,\ |\bar{f}> \to e^{i\bar{\gamma}_f}|\bar{f}>\,, \qquad (4)$$

with four independent phases γ, $\bar{\gamma}$, γ_f and $\bar{\gamma}_f$. Noting that under such a redefinition

$$A \to e^{i(\gamma-\gamma_f)}A\,,\ B \to e^{i(\bar{\gamma}-\gamma_f)}B\,,\ \bar{A} \to e^{i(\bar{\gamma}-\bar{\gamma}_f)}\bar{A}\,,\ \bar{B} \to e^{i(\gamma-\bar{\gamma}_f)}\bar{B}\,,\ \frac{q}{p} \to e^{i(\gamma-\bar{\gamma})}\frac{q}{p}\,, \quad (5)$$

we see that the only quantities which are at most quadratic in the amplitudes and which have a chance to be physical are

$$\eta,\ |A|^2,\ |\bar{A}|^2,\ |B|^2,\ |\bar{B}|^2,\ \frac{q}{p}A^*B,\ \frac{p}{q}\bar{A}^*\bar{B},\ \frac{q}{p}\bar{A}\bar{B}^*,\ \frac{p}{q}AB^*, \qquad (6)$$

where $\eta \equiv |q/p|$. Because of the possibility of the phase redefinitions (5), there are only seven independent quantities in eq. (6), five moduli and two phases. One could, for instance, eliminate $|B|^2$, $|\bar{B}|^2$, $(q/p)\bar{A}\bar{B}^*$ and $(p/q)AB^*$ from the set in eq. (6) and take η, $|A|^2$, $|\bar{A}|^2$, $|(q/p)A^*B|$, $|(p/q)\bar{A}^*\bar{B}|$, $\arg((q/p)A^*B)$ and $\arg((p/q)\bar{A}^*\bar{B})$ as a set of independent quantities. Note that instead of η very often the phase $\arg(\Gamma_{12}^*M_{12})$ is used, since η is a function of this phase and of Δm, $\Delta\Gamma$. However, in the following discussion this question of independence will not be important.

In order to study CP violation we first consider the consequences of CP invariance. If CP is a good symmetry, there exist two phases β and β_f, and a CP eigenvalue ζ_D ($\zeta_D^2 = 1$), such that

$$\begin{aligned} CP|D^0> &= e^{i\beta}|\bar{D}^0>\,, \qquad CP|\bar{D}^0> = e^{-i\beta}|D^0>\,, \\ CP|f> &= e^{i\beta_f}|\bar{f}>\,, \qquad CP|\bar{f}> = e^{-i\beta_f}|f>\,, \end{aligned} \qquad (7)$$

and

$$\begin{aligned} CP|D_H> &= \zeta_D|D_H>\,, \\ CP|D_L> &= -\zeta_D|D_L>\ . \end{aligned} \qquad (8)$$

As a result, the CP invariance conditions are

$$\bar{A} = e^{i(\beta_f-\beta)}A,\ \bar{B} = e^{i(\beta_f+\beta)}B,\ \frac{q}{p} = \zeta_D e^{i\beta},\ M_{12} = e^{-2i\beta}M_{12}^*\,,\ \Gamma_{12} = e^{-2i\beta}\Gamma_{12}^*\,. \quad (9)$$

Therefore, if CP is conserved the quantities

$$\eta^2 - 1,\ |A|^2 - |\bar{A}|^2,\ |B|^2 - |\bar{B}|^2,\ X \equiv \frac{q}{p}A^*B - \frac{p}{q}\bar{A}^*\bar{B},\ \bar{X} \equiv \frac{q}{p}\bar{A}\bar{B}^* - \frac{p}{q}AB^* \quad (10)$$

all vanish. On the other hand, if CP is not conserved the quantities in eq. (10) measure CP violation. Knowing their values means having the complete information about CP violation in D^0–$\bar{D}^0$ mixing and in the decays of $D^0/\bar{D}^0$ into the specific final states $f/\bar{f}$. Furthermore, all observables in this connection must be functions of the quantities in the set of eq. (10) and possibly of

$$|A|^2 + |\bar{A}|^2,\ |B|^2 + |\bar{B}|^2,\ \mathcal{Y} \equiv \frac{\mathrm{II}}{\surd}\mathcal{A}^*\mathcal{B} + \frac{\surd}{\mathrm{II}}\bar{\mathcal{A}}^*\bar{\mathcal{B}},\ \bar{\mathcal{Y}} \equiv \frac{\mathrm{II}}{\surd}\bar{\mathcal{A}}\bar{\mathcal{B}}^* + \frac{\surd}{\mathrm{II}}\mathcal{A}\mathcal{B}^*, \tag{11}$$

which are not CP-violating. CP-violating observables have to be odd functions of the quantities in eq. (10).

It is easy to see that $\bar{\mathcal{X}}$ is related to $\mathcal{X}$ and $\mathcal{Y}$ by

$$\bar{\mathcal{X}} = -\frac{1}{2}(\eta^2 + \frac{1}{\eta^2})\mathcal{X}^* + \frac{\infty}{\in}(\eta^{\in} - \frac{\infty}{\eta^{\in}})\mathcal{Y}^*. \tag{12}$$

As we will see below, instead of using Re$\mathcal{X}$ and Im$\mathcal{X}$ (or Re$\bar{\mathcal{X}}$ and Im$\bar{\mathcal{X}}$) as independent CP-violating observables, it is more convenient to take

$$\begin{aligned}
\mathrm{Im}\,[(\Delta m - \frac{i}{2}\Delta\Gamma)\mathcal{X}] &= -2\,\mathrm{Im}\,[M_{12}(AB^* + \bar{A}^*\bar{B})] - \mathrm{Re}\,[\Gamma_{12}(AB^* - \bar{A}^*\bar{B})]\,, \\
\mathrm{Im}\,[(\Delta m - \frac{i}{2}\Delta\Gamma)\bar{\mathcal{X}}] &= -2\,\mathrm{Im}\,[M_{12}(AB^* + \bar{A}^*\bar{B})] + \mathrm{Re}\,[\Gamma_{12}(AB^* - \bar{A}^*\bar{B})]\,. \quad (13)
\end{aligned}$$

It can be checked by using eq. (12) that both sets are equivalent if $\Delta m\Delta\Gamma \neq 0$. To derive eqs. (13) we have used eq. (3).

It is important to realize that there are three possible different kinds of CP violation in the D^0–$\bar{D}^0$ system (or any other neutral-meson system). Namely, there may be CP violation in mixing (which just means $\eta \neq 1$), direct CP violation (that is, $|A| \neq |\bar{A}|$ or $|B| \neq |\bar{B}|$), or CP violation in the relationship between mixing and decays — non-vanishing $\mathcal{X}$ or $\bar{\mathcal{X}}$. Often, authors refer to this last form of CP violation as "CP violation in mixing", but we think this designation is inappropriate. CP is violated in mixing if and only if η is different from 1, and this is independent of the decay amplitudes to any particular decay modes.

If at $t = 0$ a D^0 or a $\bar{D}^0$ is produced, then its time evolution is given by

$$\begin{aligned}
|D^0(t)> &= f_+(t)|D^0> + \frac{q}{p}f_-(t)|\bar{D}^0>\,, \\
|\bar{D}^0(t)> &= \frac{p}{q}f_-(t)|D^0> + f_+(t)|\bar{D}^0>\,, \quad (14)
\end{aligned}$$

with

$$f_\pm(t) = \frac{1}{2}e^{-i(m-\frac{i}{2}\Gamma)t}\left[e^{-\frac{i}{2}(\Delta m - \frac{i}{2}\Delta\Gamma)t} \pm e^{\frac{i}{2}(\Delta m - \frac{i}{2}\Delta\Gamma)t}\right], \tag{15}$$

where

$$m = \frac{1}{2}(m_H + m_L)\,,\ \Gamma = \frac{1}{2}(\Gamma_H + \Gamma_L)\,. \tag{16}$$

These formulae allow us to consider the time-dependent decay rates of $D^0/\bar{D}^0$. Now we address ourselves to the question of whether one can measure, at least in principle,

all the CP-violating observables in the set (10), which we derived from rephasing invariance, by considering the above-mentioned time-dependent decay rates. The answer is affirmative. In order to see this, consider the quantities [10]

$$\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to \bar{f}) = e^{-\Gamma t}\left\{|A|^2 - |\bar{A}|^2 + (\Gamma t)\,\mathrm{Im}\,[(x-iy)\mathcal{X}] + \right.$$
$$\left. + \tfrac{1}{4}(\Gamma t)^2\left[(\eta^2|B|^2 - \tfrac{1}{\eta^2}|\bar{B}|^2)(x^2+y^2) - (|A|^2 - |\bar{A}|^2)(x^2-y^2)\right] + \mathcal{O}(\sqcup^\ni)\right\},$$

$$\Gamma(D^0(t) \to \bar{f}) - \Gamma(\bar{D}^0(t) \to f) = e^{-\Gamma t}\left\{|\bar{B}|^2 - |B|^2 + (\Gamma t)\,\mathrm{Im}\,[(x-iy)\bar{\mathcal{X}}] + \right.$$
$$\left. + \tfrac{1}{4}(\Gamma t)^2\left[(\eta^2|\bar{A}|^2 - \tfrac{1}{\eta^2}|A|^2)(x^2+y^2) - (|\bar{B}|^2 - |B|^2)(x^2-y^2)\right] + \mathcal{O}(\sqcup^\ni)\right\}, \quad (17)$$

with

$$x \equiv \frac{\Delta m}{\Gamma}\,,\ y \equiv \frac{\Delta\Gamma}{2\Gamma}\,. \quad (18)$$

The terms with time dependence $e^{-\Gamma t}$ are $|A|^2 - |\bar{A}|^2$ and $|\bar{B}|^2 - |B|^2$, whereas those with time dependence $(\Gamma t\, e^{-\Gamma t})$ coincide with the quantities in eq. (13).

Taking also into account the sum of the time-dependent decay rates, the moduli of all the amplitudes are found from the terms with time dependence $e^{-\Gamma t}$. This would in principle allow the determination of η^2 from the $((\Gamma t)^2\, e^{-\Gamma t})$ contributions in eqs. (17). However, this contribution can rather be used to get information on x and y, while η is better extracted from inclusive semileptonic decays of tagged $D^0/\bar{D}^0$ by

$$\frac{\mathcal{N}_- - \mathcal{N}_+}{\mathcal{N}_- + \mathcal{N}_+} = \frac{\eta^4 - 1}{\eta^4 + 1} = \frac{\mathrm{Im}\,(\Gamma_{12}^* M_{12})}{|M_{12}|^2 + \frac{1}{4}|\Gamma_{12}|^2}\,, \quad (19)$$

where $\mathcal{N}_+\,(\mathcal{N}_-)$ is the number of positively (negatively) charged leptons originating from $\bar{D}^0(t)\,(D^0(t))$. Of course, with like-sign dilepton events from correlated $D^0\bar{D}^0$ decays $(\eta^4-1)/(\eta^4+1)$ can also be measured.

If we consider the decays to CP eigenstates $|F>$ the analysis becomes simpler. We must then make the identification

$$B \to \bar{A},\ \bar{B} \to A \quad (20)$$

in the previous formulas. Then we have $\mathcal{X} = \bar{\mathcal{X}}$ and

$$\mathrm{Im}\,[(\Delta m - \frac{i}{2}\Delta\Gamma)\mathcal{X}] = -\triangle\,\mathrm{Im}\,(\mathcal{M}_{\infty\in}\mathcal{A}\bar{\mathcal{A}}^*)\,. \quad (21)$$

We note that eq. (21) does not depend on Γ_{12} and the two eqs. (17) become identical in the case $D^0/\bar{D}^0 \to F$. Instead of the quantity on the right-hand side of eq. (21) we could take $\mathrm{Im}\,(\frac{q}{p}A^*\bar{A})$ as the CP-violating quantity which is zero if CP is conserved. Indeed, if CP is conserved, there exists a CP eigenvalue $\zeta_F = \pm 1$ such that $\mathcal{CP}|\mathcal{F}>= \zeta_\mathcal{F}|\mathcal{F}>$, with

$$\bar{A} = \zeta_F\, e^{-i\beta} A\,. \quad (22)$$

Therefore,

$$\frac{q}{p}A^*\bar{A} = \zeta_D\zeta_F|A|^2\,, \quad M_{12}A\bar{A}^* = (M_{12}A\bar{A}^*)^* \quad (23)$$

are both real.

3 The effective superweak interaction

In the SM, CP violation in the decays of $D^0/\bar{D}^0$ is extremely small. This can easily be seen when using the Wolfenstein parameterization of the KM matrix. Going beyond the SM, we assume that, either we can neglect the new contributions to the decay amplitudes and to Γ_{12}, or the new contributions to the decay of the c quark are real relative to the SM ones. On the other hand, the additional interactions enhance $M_{12} = |M_{12}|e^{i\phi}$. Then, if the phase ϕ is large, we have an effective superweak scenario with $|M_{12}| \gg |\Gamma_{12}|$, while [9, 11] all the CP-violating quantities in eq. (10) arise only from ϕ. Assuming for simplicity that Γ_{12} is exactly real and that there is no CP violation in A, B, $\bar{A}$, and $\bar{B}$,[1] we obtain

$$\Delta m \approx 2|M_{12}|\,, \qquad \Delta\Gamma \approx 2\Gamma_{12}\cos\phi\,, \tag{24}$$

and

$$\begin{aligned}
|A|^2 - |\bar{A}|^2 = |B|^2 - |\bar{B}|^2 = 0\,,\\
\mathrm{Im}\,[(\Delta m - \frac{i}{2}\Delta\Gamma)\mathcal{X}] \approx \mathrm{Im}\,[(\cdot\Updownarrow - \frac{\rangle}{\in}\cdot-)\not{\mathcal{X}}] \approx -\in \mathrm{Im}\,[\mathcal{M}_{\infty\in}(\mathcal{AB}^* + \mathcal{A}^*\mathcal{B})]\,,\\
\frac{\eta^4 - 1}{\eta^4 + 1} \approx 2\frac{\Gamma_{12}}{\Delta m}\sin\phi\,.
\end{aligned} \tag{25}$$

Since in an ESI the phase ϕ is the only source of CP violation, there must be relations among the quantities of eq. (10), as borne out by eq. (25).

Considering first CP violation in mixing, we must take into account that eq. (19) is somewhat misleading, because it hides the fact that $\mathcal{N}_+$ and $\mathcal{N}_-$ are suppressed by mixing, and really contain a factor $x^2 + y^2 \approx x^2$. Taking this into account, we see that in order to detect CP violation in mixing one has to overcome a suppression factor $\Delta m \Delta\Gamma/\Gamma^2$. In the SM we expect $\Delta\Gamma/\Gamma \sim \Delta m(SM)/\Gamma \sim 10^{-5\pm1}$; therefore, even with $x^2 \sim 10^{-2}$ at the present upper limit and $\sin\phi \sim 1$, it seems to be hard to see an effect.

Taking this crude argument into account, we observe that with an ESI only the terms linear in t inside the braces of eq. (17) are relevant:

$$\begin{aligned}
\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to \bar{f}) &\approx \Gamma(D^0(t) \to \bar{f}) - \Gamma(\bar{D}^0(t) \to f)\\
&\approx -2\,(\Gamma t\, e^{-\Gamma t})\,|AB| x \cos\delta \sin\phi\,.
\end{aligned} \tag{26}$$

The phase $\delta = \arg(AB^*)$ is induced by different final-state interactions in the amplitudes A and B, and is estimated to be [11] between 5^0 and 13^0. Therefore, $\cos\delta \approx 1$. In the case of CP eigenstates F, there is no such phase and

$$\Gamma(D^0(t) \to F) - \Gamma(\bar{D}^0(t) \to F) \approx -2\,(\Gamma t\, e^{-\Gamma t})\,|A|^2 \zeta_F\, x \sin\phi\,. \tag{27}$$

The best final-state candidates to search for mixing and CP violation are probably $f = K^-\pi^+/\bar{f} = K^+\pi^-$, with branching ratios [14] $\mathrm{BR}(D^0 \to K^-\pi^+) = (4.01 \pm 0.14) \cdot 10^{-2}$ and $\mathrm{BR}(D^0 \to K^+\pi^-) = (3.1 \pm 1.4) \cdot 10^{-4}$, respectively,[2] and $F = K^+K^-$, with

[1] This amounts to CP conservation in the interactions relevant for the decays, with a phase convention $\beta = \beta_f = 0$ in eq. (7).

[2] See, however, the remarks to the latter value in refs. [3, 14].

$\zeta_F = 1$ and $\mathrm{BR}(D^0 \to K^+K^-) = (4.54 \pm 0.29) \cdot 10^{-3}$. The sensitivity of these final states to CP violation is nearly the same, because

$$\frac{\mathrm{BR}(K^+K^-)}{\sqrt{\mathrm{BR}(K^-\pi^+)\mathrm{BR}(K^+\pi^-)}} = 1.29 \pm 0.30\,. \tag{28}$$

For $f = K^-\pi^+/\bar{f} = K^+\pi^-$ the decay rates are usually normalized to the number of Cabibbo-allowed decays. We thus consider the distribution in decay time

$$\frac{[\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to \bar{f})]dt}{\int_0^\infty [\Gamma(D^0(t') \to f) + \Gamma(\bar{D}^0(t') \to \bar{f})]dt'} \approx \frac{[\Gamma(D^0(t) \to \bar{f}) - \Gamma(\bar{D}^0(t) \to f)]dt}{\int_0^\infty [\Gamma(D^0(t') \to f) + \Gamma(\bar{D}^0(t') \to \bar{f})]dt'} \approx$$

$$\approx -\left[\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}\right]^{1/2} x \cos\delta \sin\phi\, \Gamma t\, e^{-\Gamma t} d(\Gamma t)\,. \tag{29}$$

Experimentally, the bound on x is roughly $1/10$. Therefore, with $10^3 - 10^4$ Cabibbo-allowed decays, or 10–100 doubly-Cabibbo-suppressed decays, and with decay-time information, it might be possible to constrain $x \sin\phi$ beyond the trivial constraint $|x \sin\phi| \leq x$. The effect of CP violation with an ESI in the determination of mixing from $\Gamma(D^0(t) \to \bar{f}) + \Gamma(\bar{D}^0(t) \to f)$ has been studied in refs. [10, 11]. It was found that, at the present level of accuracy, it is included in the experimental errors [11].

For $F = K^+K^-$ we use the normalization

$$\frac{[\Gamma(D^0(t) \to F) - \Gamma(\bar{D}^0(t) \to F)]dt}{\int_0^\infty [\Gamma(D^0(t') \to F) + \Gamma(\bar{D}^0(t') \to F)]dt'} \approx -x \sin\phi\, \Gamma t\, e^{-\Gamma t} d(\Gamma t). \tag{30}$$

Here we estimate that $10^2 - 10^3$ K^+K^- events would probably give a useful constraint on $x \sin\phi$.

4 Conclusions

We have done a systematic study of CP violation in tagged $D^0/\bar{D}^0$ decays, in which we have identified all the rephasing-invariant observables which measure CP violation in the decays to a final state f and its antiparticle state $\bar{f}$, or to a CP eigenstate F. These quantities, which parameterize the complete information on CP violation in this context, are constructed from the mixing parameter q/p and from the decay amplitudes, and therefore depend on the specific final state. We have shown that by studying the time-dependent decay rates of $D^0/\bar{D}^0$ to $f/\bar{f}$ or to F one can, in principle, measure all the CP-violating observables which we have identified. The D^0–$\bar{D}^0$ system is unique (see [5] for a nice presentation of this fact), in comparison to the K^0–$\bar{K}^0$ and B^0–$\bar{B}^0$ systems, in that x and y are both much smaller than one. As a consequence, one can expand the time-dependent decay rates in terms of $(\Gamma t)^n\, e^{-\Gamma t}$ $(n = 0, 1, \ldots)$, and it is probably sufficient to keep only terms with $n \leq 2$. It is crucial for our analysis that experimentally the coefficients of the terms with $n \leq 2$ can be extracted.

Although our analysis is model-independent, we have considered the special case of the ESI hypothesis, which assumes that physics beyond the SM does not contribute

significantly to the $D^0/\bar{D}^0$ decay amplitudes, but gives the dominant contribution to M_{12}, with an unsuppressed CP-violating phase $\phi \equiv \arg M_{12}$. Under this assumption, we have tried to assess the sensitivity of experiments with decay-time information to CP violation. Thereby we have compared CP non-eigenstates (where one has Cabibbo non-suppressed versus doubly-Cabibbo-suppressed amplitudes) with CP eigenstates (single Cabibbo suppression). We have seen that experimental information on CP violation restricts (or determines) the quantity [9] $x \sin\phi$, and the upper limit obtained for this quantity must be smaller than the upper limit on x, in order to get a non-trivial restriction in the $x - \phi$ plane. In the case of x close to its upper bound, we have estimated the numbers of events necessary for this purpose. They seem to be well within the range of current and future search for D^0–$\bar{D}^0$ mixing [3]. Of course, an experimental determination of $x \sin\phi$ would not only prove the existence of CP violation in the D^0–$\bar{D}^0$ system, but also give a lower bound on the mixing parameter x.

References

[1] I.I. Bigi, in Proc. of the Tau-Charm Factory Workshop, SLAC, May 23-27, 1989, SLAC-Report-343, p. 169.

[2] G. Burdman, preprint FERMILAB-Conf-95/281-T, talk delivered at the Workshop on the Tau/Charm Factory, Argonne, June 21-23, 1995.

[3] T. Liu, preprint HUTP-94/E021, to appear in the Proc. of the Charm 2000 Workshop, Fermilab, June 7-9, 1994.

[4] A. Datta and D. Kumbhakar, Z. Phys. C 27 (1985) 515.

[5] See, for instance, E. Golowich, preprint UMHEP-419, talk delivered at XXX$^{\text{ième}}$ Rencontre de Moriond, Les Arcs, March 19-26, 1995.

[6] L. Wolfenstein, Phys. Lett. B 164 (1985) 170;
J.F. Donoghue, E. Golowich, B.R. Holstein and J. Trampétić, Phys. Rev. D 33 (1986) 179.

[7] H. Georgi, Phys. Lett. B 297 (1992) 353.

[8] T. Ohl, G. Ricciardi and E.H. Simmons, Nucl. Phys. B 403 (1993) 605.

[9] L. Wolfenstein, Phys. Rev. Lett. 75 (1995) 2460.

[10] G. Blaylock, A. Seiden and Y. Nir, Phys. Lett. B 355 (1995) 555.

[11] T.E. Browder and S. Pakvasa, preprint UH 511-828-95.

[12] G.C. Branco, P.A. Parada and M.N. Rebelo, Phys. Rev. D 52 (1995) 4217;
Y. Nir and N. Seiberg, Phys. Lett. B 309 (1993) 337;
L. Hall and S. Weinberg, Phys. Rev. D 48 (1993) R979.

[13] A. Le Yaouanc, L. Oliver and J.-C. Raynal, Phys. Lett B 292 (1992) 353.

[14] Particle Data Group, Phys. Rev. D 50 (1994) 1173.